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13. ABSTRACT (Maximum 200 words)
The objective of this research project was to quantify the response of shocked ceramics, including strength in the shocked state, to understand the mechanisms governing inelastic deformation at high stresses and high strain-rates in these materials. In-situ, piezoresistance stress gauge measurements were obtained in dense, polycrystalline silicon carbide (SiC) samples subjected to plane wave loading. A significant effort was carried out to ensure a self-consistent analysis of the lateral piezoresistance gauge data. Analysis of the longitudinal data revealed an inelastic response that could be modeled using either a strain hardening, plasticity model or a pressure-dependent strength model with stress relaxation. Experimental measurements and analysis of the lateral gauge data in SiC, currently underway, are needed to develop a comprehensive understanding of shocked SiC. Preliminary experiments and numerical calculations were completed to undertake combined compression and shear wave measurements in the SiC. The use of lateral piezoresistance gauges, and compression-shear measurements provide independent corroborations of material strength in the shocked state. This determination is important for understanding the differences in the compressive and tensile response of shocked ceramics.

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FOREWORD

This report summarizes the work carried out under the Army Research Office Grant DAAL 03-92-G-0145 through June 30, 1995; discussions with Drs. Kailasam Iyer and John Bailey (Project Monitors) were most helpful. The author sincerely acknowledges the contribution of the following individuals: Dr. D.P. Dandekar (ARL) who provided the samples used in this study and shared valuable insight into the SiC response based on his tension work; Dr. D.E. Grady (Sandia) provided us with his high pressure data on SiC; Dr. J.N. Johnson (Los Alamos)'s visit to W.S.U. resulted in many valuable discussions and was most helpful in incorporating a simplified version of his microcracking model in our numerical calculations. At W.S.U., the following individuals contributed to this effort: Dr. R. Feng, Dr. G. Raiser, D. Savage and K. Zimmerman. They are thanked for their participation and numerous contributions.

I. STATEMENT OF THE PROBLEM

A good understanding of shock-induced inelastic deformation of ceramics and its relationship to material microstructure is important for the use of these materials in a variety of projectile impact applications. An important scientific challenge is how to probe the strength properties in the shocked state, and to identify and understand the inelastic deformation mechanisms operative at these extreme loading conditions. To meet this objective we have developed and utilized in-situ, time-resolved, stress measurements in polycrystalline silicon carbide samples subjected to plane shock waves. Results and related analyses are summarized here.

II. SUMMARY AND ACCOMPLISHMENTS

A. Material Selection

Since an in-depth examination of a single material was an important thrust of our research effort, input was sought from scientists at ARL (Watertown, MA), BRL, Sandia Labs, and Los Alamos. On the basis of their recommendations, dense polycrystalline silicon carbide (SiC) was selected for our work. Based on an analysis of their high stress VISAR measurements and an assumed hydrodynamic response, Grady and Kipp had suggested that this material retains strength in the shock compressed state.[1] We chose to carry out our experiments on the SiC (type B) samples manufactured by Cercom Inc. of Vista, California. All of the samples used in our work were cut from blocks that were provided by ARL (courtesy of Dr. D.P. Dandekar). This usage ensured that we could coordinate our work with that at ARL and at Sandia. Because the experimental work at ARL (tension studies) and Sandia (very high stress measurements and examination of different ceramics) was complimentary to our effort, the choice of SiC was deemed mutually beneficial.

B. Shock Response of SiC

A detailed examination of inelastic deformation in shocked SiC at the continuum level was the main theme of our current project. Additionally, we chose to conduct experiments with peak stresses in the 10 to 23 GPa range. Because the HEL for the SiC used in our work was reported to be approximately 11.5 GPa,[2] we wanted to examine a stress range where the effects due to inelastic deformation would be most pronounced. For ease of discussion, we summarize our results in four parts.

1. Longitudinal Measurements and Analyses

Plate impact experiments utilizing quartz gauges or in-material, manganin gauges were performed on samples for peak stresses between 7.3 to 23 GPa. The in-material, manganin gauge results above the reported HEL show the material response to be inelastic. Using an impedance matching method, stress-particle velocity values corresponding to the peak states were obtained and a single curve could be fitted to all of our data and the high stress data from Sandia Labs.[1,2] Two different continuum models (strain-hardening, plasticity model by Grady and Kipp,[1] and a pressure dependent strength model with stress relaxation) were used to simulate the measured profiles in our work and the Sandia data. Although both models gave reasonably good agreements, our pressure dependent model provided a better fit. Preliminary calculations were also carried

out using a simplified version of the Addessio and Johnson microcracking model[3] and, again, reasonable agreement was obtained. Regarding the microcracking model, further work is needed.

This work has provided a detailed set of longitudinal measurements and a consistent shock Hugoniot for the Cercom SiC over a wide stress range (7 to 50 GPa). Both the end states and the in-material profiles can be fitted by a number of material models that are qualitatively different. *The longitudinal data by themselves do not provide sufficient constraints to uniquely decompose the longitudinal stress into mean stress and stress deviators.* Although the effort expended for the longitudinal measurements and analyses for SiC was necessary and valuable, it does not provide definitive information about the strength in the shocked state. This issue is addressed using the experiments outlined below.

Regarding the longitudinal measurements, one final comment is noteworthy. The work at Sandia Labs. has also examined SiC from Eagle-Picher. This material has a somewhat different microstructure and a HEL that is 20 percent higher than the Cercom material.[2] However, the peak states (3 points between 25 and 50 GPa) reported by Grady and Kipp[1] are in excellent agreement with the Hugoniot we have determined for the Cercom material. Thus, at the very high stresses, the shocked state does not appear to be influenced by the HEL value of the starting material.

2. Analysis of In-Material Lateral Gauge Measurements

The difficulty in fully characterizing the continuum state using longitudinal measurements has been indicated above. Given that the question of strength retention or strength loss in the shocked state is an important one for brittle materials, a central element of our work was to experimentally determine the material strength (or stress deviators) in the shocked state. We chose to do so using two independent methods: use of lateral piezoresistance gauges, and compression and shear wave measurements. The work based on these two methods is summarized in items 3 and 4 below.

Before discussing the lateral gauge results in item 3 below, a brief discussion of the analysis of the lateral gauge data is in order. Since 1977, the author and his coworkers have been working on a detailed understanding of longitudinal and lateral piezoresistance gauges. A concise summary of this work can be seen in Reference 4. The main findings from our work may be stated as follows: (i) lateral gauge response though dominated by the matrix lateral stress depends on several factors, (ii) unlike the longitudinal gauge response which can be validated through the momentum equation, there is no fundamental method to validate the lateral gauge response, (iii) a recent comprehensive study by M. Wong has provided a numerical method to analyze the dynamic response of embedded lateral gauges in plate impact experiments.[5]

Given the importance of the material strength issue and the need for a rigorous analysis of the lateral gauge data, a significant effort was undertaken to analyze the lateral gauge data. The goal of this effort was to find an analytic method to invert the gauge data *with confidence* and to be able to put some error bars on the final result. Although the approach used in Mike Wong's thesis can always be utilized (that is, -- assume a material model for the matrix and carry out 2-D code calculations and iteratively match the strength model to the experimental results), we decided that such an approach was impractical for every experiment. We wanted to find a simpler method for

data analysis and yet determine the limitations of the simpler method by comparing the results with rigorous 2-D numerical solutions. This task turned into a large effort. However, the work has progessed very well and will be published at a future date. This effort has been extremely valuable in detailing what can and cannot be learned from lateral gauge data in ceramics. Some of the important findings to date are as follows:

(i) Analysis of the complete time-dependent response of lateral gauges is a complex problem and many of the transient features in the data are governed by a coupling of the material behavior and gauge emplacement conditions (including bond thickness). Relating the breaks in the profiles directly to the ceramic response can lead to significant errors, e.g. inference of HEL from lateral gauge data should be avoided.

(ii) Comparing the transient response of longitudinal and lateral gauges is not meaningful. Simpler analyses are possible only for that part of the lateral gauge data which shows a constant or flat top response.

(iii) Simpler analyses need to be checked against the more rigorous dynamic analyses. It is possible to develop a method of analysis that may be used for ceramic materials. Extension of the same analysis for other materials requires care.

(iv) The lateral gauge data corresponding to the constant state can be analyzed to obtain the lateral stress in the ceramic material. Hence, questions regarding strength retention or loss can be addressed by suitable design of experiments: use of long pulse durations and appropriate gauge emplacement.

3. Determination of Lateral Stresses in Shocked SiC

We have carried out an extensive series of experiments with embedded, lateral manganin gauges in SiC samples. Gauges were mounted on ground SiC surfaces and the epoxy bond thicknesses were carefully controlled to minimize perturbations to the propagating shock wave. Both one and two gauge experiments were conducted and data were obtained over the same range as the longitudinal gauges. Analysis of these data are being completed and a manuscript detailing these results will be published at a future date.

The most reliable result from these measurements is a determination of the matrix lateral stress in the shocked state for sufficiently long pulse durations. We have also carried out detailed 2-D simulations of the lateral gauge output (resistance change histories) to support our data analysis. *The principal finding from this extensive set of measurements is that the Cercom SiC retains material strength beyond HEL up to a peak longitudinal stress of 230 kbar.* Thus, our results provide direct confirmation of material strength in shocked SiC. Although similar inferences had been made earlier,[1] these were based on an assumed mean stress-volume curve for the SiC. Given the possible uncertainties in the mean stress-volume curves, inferences from the longitudinal data alone need to be viewed with caution.

Strength retention in shocked SiC, though an important result, does not rule out

microcracking mechanisms similar to those considered by Addessio and Johnson.[3] Given the large confinement due to uniaxial strain loading, significant material strength can occur in a material undergoing microcracking. The tensile measurements in SiC show spall strengths which decrease with peak stress beyond HEL.[1,6] This finding along with our data would suggest inter-granular deformation (likely microcracking) but it cannot be taken as unequivocal evidence. Finally, our results raise the question: if microcracking is the mechanism for inelastic deformation, then does this occur during loading to the peak state or upon unloading because of a decrease in confinement. A more definitive answer to this question will be sought in future work.

4. Combined Compression and Shear Measurements in SiC

We emphasize the need for determining material strength using independent methods to lend strong confidence to such a determination. The second method we chose involved in-material measurements of combined compression and shear wave propagation in SiC samples. This part of our experimental work is currently in progress. To date, we have completed the following tasks:

(i) Experimental methods have been developed to embed multiple gauges to obtain compression and shear measurements.

(ii) Two experiments have been carried out to demonstrate that shear wave velocities can be measured in the shocked state with good precision.

(iii) A computational effort was undertaken and successfully completed to analyze the propagation of large amplitude shear waves through SiC layers bonded with thin epoxy films. Such an analysis is a prerequisite for analyzing the shear wave amplitude data from our experiments.

C. Concluding Remarks

The objectives for the current project were successfully addressed. As with any fundamental research effort, every activity did not succeed as planned. Working out the experimental techniques for both piezoresistance gauges and particle velocity gauges took longer than anticipated. Analyses of the lateral gauge data turned into a major effort because of the numerical complexities associated with simulating a gauge on the SiC surface. However, it was deemed necessary to develop a rigorous approach for analyzing these data. The work completed in the current project provide a sound basis for the work currently underway to understand inelastic deformation in shocked ceramics.

D. References

1. M.E. Kipp and D.E. Grady, in "Shock Compression of Condensed Matter-1989", p. 377 (Elsevier, 1990); Sandia Report No. SAND92-1832, Sandia Labs., Albuquerque, N.M. 1993.

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3. F.L. Addessio and J.N. Johnson, J. Appl. Phys. 67, 3275 (1990).

4. Y.M. Gupta, in "Experimental Techniques in the Dynamics of Deformable Solids", pages 89-101, Ed. K.T. Ramesh, AMD Vol. 165 (ASME, NY, 1993).

5. M.K.W. Wong, Ph.D. Thesis, Washington Sate University (1991).

6. D.P. Dandekar, private communication.

III. LIST OF PUBLICATIONS AND PRESENTATIONS

Papers:

1. "Use of Piezoresistance Gauges to Quantify the Stress State in a Shocked Solid," Y.M. Gupta, in *Experimental Techniques in the Dynamics of Deformable Solids,* Ed. K.T. Ramesh, pages 89-101, AMD-Vol. 65 (ASME, NY 1993).

2. "Effect of Epoxy Bond Response on Combined Compression - Shear Wave Propagation in Solids," R. Feng and Y.M. Gupta, in *High-Pressure Science and Technology - 1993,* p. 1127 (AIP, New York, 1994).

3. "Shock Response of Silicon Carbide Undergoing Inelastic Deformation," R. Feng, G.F. Raiser, and Y.M. Gupta, J. Appl. Phys. 79(3), 1378 (1996).

Presentations:

1. Y.M. Gupta, "Use of Piezoresistance Gauges to Quantify the Stress State in a Shocked Solid," Symposium on Experimental Techniques in the Dynamics of Deformable Solids; SES/ASME/ASCE Joint Conference, University of Virginia, Charlottesville, VA (June 1993).

2. Y.M. Gupta, "Characterizing the Shocked State in Brittle Solids," ARO Workshop on Dynamic Behavior of Brittle Materials; Brown University, Providence, RI (July, 1993).

3. Y.M. Gupta, "Determination of Material Strength in Shocked Ceramics", Army Symposium on Solid Mechanics, Plymouth, MA (August, 1993); presentation made by Dr. D.P.Dandekar (ARL) because of a conflict with another meeting.

4. Y.M. Gupta, "Combined Compression and Shear Wave Propagation in Piezoelectric Crystals," IUTAM Symposium on Nonlinear Waves in Solids, University of Victoria, Victoria, B.C., Canada (August 1993).

5. R. Feng, G.F. Raiser, and Y.M. Gupta, "Determination of Dynamic Strength of Silicon Carbide," presentation at the 12th U.S. National Congress of Applied Mechanics (Seattle, WA., 1994).

6. Y.M. Gupta, R. Feng, and G.F. Raiser, "Inelastic Response of Shocked Silicon Carbide", presentation at the 31st Annual Meeting of the Society of Engineering Science (College Station, Texas, 1994).

IV. LIST OF PARTICIPATING SCIENTIFIC PERSONNEL

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V. INVENTIONS

None